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ESTUDIO DEL EFECTO DE TRATAMIENTOS MAGNÉTICOS EN LA FISIOLOGÍA Y EL RENDIMIENTO DE DIFERENTES ESPECIES

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Study of the effect of magnetic treatments on the physiology and yield of different crop species

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A mi madre

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Resumen

En este estudio se evaluó la hipótesis de que el tratamiento magnético de semillas y aguas de riego afecta el comportamiento fisiológico de diferentes especies de ciclo corto. Se partió de investigaciones anteriores donde dichos tratamientos generaron beneficios tangibles en el rendimiento de cosecha. El objetivo de este trabajo fue entonces estudiar los parámetros fisiológicos y el rendimiento en cuatro especies de ciclo corto (tomate, rábano, maíz y ají) después de un pretratamiento magnético a las semillas y durante el desarrollo con agua tratada magnéticamente, en diferentes condiciones experimentales (sistema hidropónico controlado y casa de malla). Entre las variables principales se analizaron la tasa de germinación, fotosíntesis, fluorescencia de la clorofila, condición hídrica y acumulación de biomasa. También se evaluaron las propiedades fisicoquímicas del agua tratada magnéticamente. Los resultados mostraron que el pretratamiento magnético de semillas produjo un beneficio marginal en el vigor y el porcentaje de germinación. En contraste, el tratamiento magnético del agua provocó incrementos significativos en la fotosíntesis, el potencial hídrico y la conductancia hidráulica de la raíz. Estos efectos fueron consistentes con una mayor acumulación de biomasa y nutrientes en diferentes órganos, así como una mayor tolerancia al estrés hídrico. Sin embargo, estas respuestas no fueron significativas para todas las especies evaluadas. Se concluye que los efectos fisiológicos en la germinación de semillas con pretratamiento magnético dependen del mecanismo del par radical en reacciones enzimáticas. Por otra parte, la reducción en la tensión superficial del agua tratada magnéticamente estimularía el proceso de transporte hídrico desde las raíces hasta las hojas, lo cual favorece el crecimiento y desarrollo vegetal.

Palabras clave: actividad del agua, biomasa, germinación, fotosíntesis, magneto-biología, mecanismos enzimáticos, tensión superficial.

Abstract

In this study it was evaluated the hypothesis that the magnetic treatment of seeds and irrigation water affects the physiological performance of different short-cycle crop species. This was based on previous reports where these treatments generated tangible benefits in the crop yield. The objective of this work was, hence, to study the physiological parameters and yield in four short-cycle species (tomato, radish, maize and pepper) after a magnetic pretreatment to the seeds and during growth with magnetically-treated water under different conditions (controlled hydroponic system and net house). Among the main variables, the germination rate, photosynthesis, chlorophyll fluorescence, water status and biomass accumulation were analyzed. The physicochemical properties of magnetically-treated water were also evaluated. The results showed that the magnetic pretreatment of seeds produces a marginal benefit in the vigor and germination percentage. In contrast, the magnetic treatment of water caused significant increases in photosynthesis, water potential and root hydraulic conductance. These effects were concomitant with a greater accumulation of biomass and nutrients in different organs, as well as a greater tolerance to water stress. However, these responses were not significant for all the species evaluated. It is concluded that the physiological effects on germinating seeds with magnetic pretreatment depend on the radical-pair mechanism in enzymatic reactions. On the other hand, the reduction in the surface tension of the magnetically-treated water would stimulate the water transport process from the roots to the leaves, which enhances the growth and development.

Keywords: biomass, enzymatic mechanisms, germination, magneto-biology, photosynthesis, surface tension, water activity.

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Symbol	Term	Unit	Definition
A	Net photosynthesis	µmol CO_2 m^{-2} s^{-1}	Net uptake of CO_2 into the leaf
E	Transpiration rate	mmol H_2O m^{-2} s^{-1}	Evaporation of water from the leaf surface
EL	Electrolyte leakage	%	Ratio of ions released from a tissue
F_0	Minimal fluorescence from dark-adapted leaves	Absorbance units	Idem of term
F_m	Maximum fluorescence in dark-adapted leaves	Absorbance units	Idem of term
F_v	Variable fluorescence	Absorbance units	$F_m – F_0$
F_v/F_m	Maximum quantum yield of PSII photochemistry	-	Idem of term
F_v'/F_m'	PSII maximum efficiency	-	Idem of term
F_0/F_m	Quantum yield base line	-	Idem of term
g_s	Stomatal conductance from water to vapor	mol H_2O m^{-2} s^{-1}	Rate of gas exchange through the leaf
K_r	Root hydraulic conductance	m^3 m^{-1} s^{-1} MPa^{-1}	Water conductance through roots
LAR	Leaf area ratio	cm^2 g^{-1}	Ratio of leaf area to dry biomass
MF	Magnetic field	mT (mili Tesla)	A region of the space where a charged particle suffers a force (Lorentz force)
NPQ	Non-photochemical quenching	-	$(F_m/F_m') – 1$.
PAR	Photosynthetic active radiation	µmol quanta m^{-2} s^{-1}	Light intensity at 400 – 700 nm
RWC	Relative water content	%	Ratio of water at leaf full turgor to a given water content
qP	Photochemical quenching	-	$(F_m' - F_S)/(F_m' – F_0')$
SLA	Specific leaf area	cm^2 g^{-1}	Leaf area per unit of leaf dry biomass
WUE	Water use efficiency	µmol CO_2/mmol H_2O	CO_2 taken up per unit of H_2O transpired
Φ_{PSII}	PSII operating efficiency	-	F_q'/F_m'
Ψ_{leaf}	Leaf water potential	Mpa	Free energy of water per unit volume

Abbreviations

Abbreviation	Term
MTW	Magnetically-treated water or Magnetic treatment of water

Introduction

One of the alternative methods to increase crop yield is the improvement of the physiological conditions of the seeds by priming before sowing, such as osmopriming with osmotic substances (Mouradi et al., 2016) and hydropriming by water soaking (Matsushima and Sakagami, 2013) which generally confer increased tolerance to subsequent abiotic stressors and higher vigor. The magnetic treatment of seeds, or magnetopriming, is a technique that has been evaluated in horticultural species, exhibiting a faster germination, more vigorous seedlings with a better-developed root system and higher growth rate (Mridha et al., 2016; Shine et al., 2011; Vashisth et al., 2010b). This is related with an increase in the activity of hydrolytic enzymes and an increase in water uptake, which explains the effects in the germination phase. In addition, several works report deferred benefits in fruit set and quantum efficiency of photosynthesis in plants emerged from magnetoprimed seeds.

As for magnetic treatment of water, the investigation reveals that a consistent use of it can lead to an augment in nutrient uptake and biomass yield in different species (Mahmood and Usman, 2014; Maheswari and Grewal, 2009). However, these findings are not supported in a coherent physiological model that explains these effects based on the physicochemical changes of magnetically-treated water. Therefore, a relationship with key factors such as gas exchange parameters, water transport and source-sink dynamics is needed.

The increasing pressure on natural resources for food production is a phenomenon that is undermining the environmental sustainability of Colombia. The more frequent occurrence of catastrophic El Niño and La Niña events are evidence of that. The scarcity of surface water and groundwater is getting severe in many farmlands, as well as soil erosion. On the other hand, the high cost of fertilizers and the lack of farm subsidies makes uncompetitive to produce several crops in Colombia. Hence, the deployment of alternative technologies of low environmental impact for yield improvement are highly encouraged.

Although some research institutes and companies have developed different magnetic treatments for seed and water, in Colombia and other countries this technology is in general unknown, because of the lack of studies in many varieties of cultivated species, the great variability among magnetic devices for treatment and some mistrusts on its reliability as plant growth enhancers. Therefore, and considering the importance of the horticultural crops in the Cauca Valley region of Colombia, it is necessary to make a quality contribution in this field, taking into account the variables little studied or disregarded until the present. The following are the hypothesis and objectives proposed for this work to meet the latter requirements.

Research hypothesis

The magnetic treatment of seeds and water affects physiological processes and yield in different short-cycle species.

Objectives

General

To study the physiological performance and final yield in different species subjected to magnetic treatments.

Specifics

To compare the water transport, gas exchange and germination process in different species developing under magnetic treatment of water or seeds.

To propose a plausible physiological action mechanism of magnetic treatments in plants.

To suggest a practical methodology for magnetic treatment of water and seeds in species of horticulture importance

Layout of the document

This paper is divided in five sections, starting from the literature review of the subject and going through the experimental part, having each of them its own set of conclusions. The contributions to the methodological and scientific aspects of the magnetic treatment for seeds and water can be shown as follows:

Chapter 1 is a thorough and published review of the most important studies on the issue of magnetic treatments of seeds and water in agriculture.

Chapter 2 shows the results, conclusions and difficulties in the application of magnetic treatments to seeds of Habanero and Tabasco pepper.

Chapter 3 evaluates a novel methodological approximation through experiments in hydroponics system with magnetically-treated water in tomato.

Chapter 4 goes through the physiological and yield responses of Tabasco pepper, yellow maize and red radish, cultivated in pots with soil in net house, and irrigated with magnetically-treated water.

Chapter 5 shows the findings of the interaction between magnetically-treated water and two levels of irrigation in Tabasco pepper, based on the physical properties of the treated water used for irrigation. A relationship between surface tension and water transport in plants is provided.

Finally, in **annex 4** there is a theoretical proposal that links the mechanical aspects of a fluid with the magnetic effects of an external magnetic field, as a contribution to the physical understanding of magnetic fields on water.

1. Magnetic treatment of irrigation water and seeds in agriculture[1]

[1] This section with few modifications was published as a review article in: Revista Ingeniería y Competitivad 18(2), 217-232, 2016.

2. Effect of static and variable magnetic fields on the germination of Tabasco and Habanero pepper seeds

2.1. Abstract

Two experiments were carried out in order to evaluate the effect of static and variable magnetic fields (MF) on the germination of seeds of Tabasco pepper (*Capsicum frutescens* L.) and Habanero pepper (*Capsicum chinense* Jacq.). The lots of pepper seeds were obtained from fruits of a six-month old commercial crop. The seed quality parameters were established prior to the experiments, as germination percentage and vigor index. For the magnetic treatments, a coil and an electromagnet coupled to a voltage regulator were used, in a factorial design from 10 mT to 100 mT for ten to thirty minutes of exposition. Subsequently, the germination process was followed according to the methodology of AOSA (2009). The results showed that a combination of 25 mT for ten minutes with variable MF produces a significant increase in the germination percentage, although vigor index was statistically equal. By contrast, treating the seeds with static MF, regardless of the intensity and exposition time, produced a non-significant decrease in the percentage of germination and vigor of seeds. Unlike to what has been reported in other species, static magnetic fields do not exert any positive effect on the germination of pepper seeds. However, a short exposition to a variable MF of 25 mT enhance the germination and vigor of Habanero pepper seeds.

2.2. Introduction

Pepper agroindustry is getting increasing importance in Valle del Cauca province of Colombia, due to its exportation potential and the existence of optimal agronomic conditions. For Tabasco pepper cultivation, a warm, dry, highly irradiated weather is very suitable, which is predominant in most of the flat portion of the department. Habanero pepper is cultivated in a quite temperate climate, which is present in the medium-mountain region of the western and central range of the Andes. Regarding exports of spicy products derived of pepper, Valle del Cauca is the leader in Colombia, both by volume and value, with 90.2 % and 80.2 % of the total national pepper exports in 2014 (Cámara de Comercio de Cali, 2015).

The cultivation of this species first starts at a nursery stage, where the seeds are sown in order to obtain vigorous and sound plantlets to be transplanted in the field. Hence, it is critical to achieve a high and uniform germination. Depending of the cultivar, the yield of pepper could reach 9 $t.ha^{-1}$, although this value is not always achieved because of the lack of suitable technologies at the nursery stage, among other issues (Rodríguez-Araujo et al., 2010).

This is the reason why the evaluation of magnetic treatments of pepper seeds is needed, taking into account that this technology has shown to produce many positive effects in germinating seeds, related with an enhancement of the enzymatic activity and water uptake (Zúñiga et al., 2016a). The main objective of this work is to assess the feasibility of different magnetic treatments to increase the germination percentage and vigor of Habanero and Tabasco pepper seeds. As specific objective, this work aims to determine whether a variable or static MF is better to produce such responses, as well as the intensity and exposition time of the seeds.

2.3. Methods

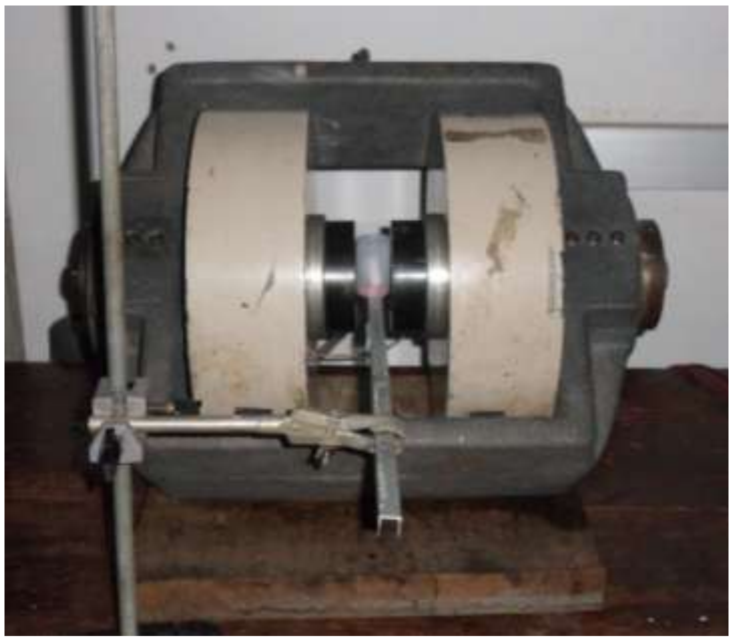
2.3.1. Plant material

Two batches of seeds of Tabasco pepper (*C. frutescens*) and Habanero pepper (*C. chinense*) were kindly provided and certified by the company Hugo Restrepo and Co. SAS. From each batch, a subsample was extracted to establish the moisture content, the percentage of germination and viability by tetrazolium test.

2.3.2. Magnetic device for seed treatment

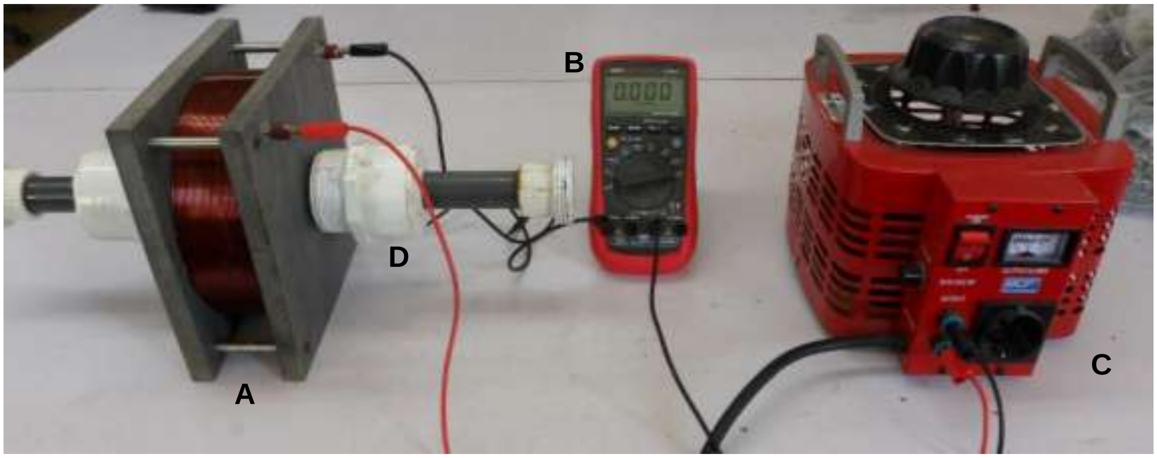
The device for magnetic treatment consisted of an electromagnet (CENCO Instruments Corporation), located at the Laboratory of Modern Physics of Valle University. This equipment generates a continuous and static MF up to 300 mT (Figure 3-1). The space between the two poles was adjusted at a distance of 3 cm. The MF intensity was tuned through a variable transformer, which also turned the alternating current (AC) to direct current (DC) hence, generating a static MF. This was measured with a fixed Teslameter (Phywe Electronics) in the center of the poles. Magnetic induction was established at 10, 20, 30, 40, 60, 80 and 100 mT for 10, 20 and 30 min, giving 21 treatments plus one control.

Figure 2-1: Aspect of the CENCO electromagnet and the seed placing in the middle.



For variable MF, it was used a solenoid consisting of 20 layers with copper wire number 14, with 57 turns per layer. The length of the coil was 10 cm and the diameter of its core was of 7.6 cm (Figure 3-2). The circuit was completed with an ammeter for measuring the current and a power supply connected in series. The frequency of the MF was the same of the alternating current (60 Hz). A water cooling system was adapted in the core of the solenoid in order to regulate the temperature during exposition of the seeds. The seeds were placed in a plastic capsule in the center of the solenoid, and subjected to MF of 25 mT and 50 mT during 10 and 20 minutes. The control seeds were settled in the same place but without turning on the electromagnet or the solenoid.

Figure 2-2: Arrangement of the solenoid for variable MF. A: solenoid. B: ammeter. C: variable power supply. D. Water cooling pipes.



2.3.3. Analysis of germination

For germination analysis, it was applied the methodology of rolled paper. Twenty-five seeds in four replications for each treatment were placed on moistened germination paper with distilled water, covered with another layer of moistened paper. The rolls were sprayed with 0.5 % NaClO to prevent fungal contamination, and stored in resealable plastic bags with holes, then placed in an incubator at 25 ° C in darkness. Two readings of germination were done at 7 and 14 days. At this time, the seedlings were blotted and weighed for fresh weight. Immediately after, seedlings were dried for 48 h at 75 ° C to measure dry weight. From these values, a vigor index (VI) was calculated, according to Abdul-Baki and Anderson (1973)

$$VI = \%\ germination * dry\ weight$$

2.3.4. Statistical analysis

Each germination test (four tests of 25 seeds each) representative of each magnetic treatment, and the control, was repeated on four different days, which resulted in a repeated measurements design, with percentage of germination and vigor index as response variables. In total, for each treatment and control were analyzed 400 seeds. The data was processed in IBM SPSS Statistics 22 by ANOVA, previously checking the homogeneity of variances and then comparing the means by Duncan test at a significance of 0.05.

2.4. Results and discussion

The results regarding the treatment of Tabasco seeds with static MF did not show any significant difference between all the combinations of magnetic induction and exposition time, either in germination percentage and vigor index. However, it worth noting that practically all the magnetic treatments decreased the germination percentage when comparing with the control, despite the higher vigor of seedlings emerged from some treatments between 20 mT and 100 mT. Tables 3-1 and 3-2 summarizes these results.

Table 2-1: Germination and vigor index in Tabasco pepper seeds treated with static MF.

Tabasco pepper			**Tabasco pepper**		
Duncan	**Germination %**	**Treatment**	**Duncan**	**VI**	**Treatment**
A	75,75	40 mT 10 min	A	1,031	80 mT 20 min
A	**75,44**	**Control**	A	1,002	100 mT 30 min
A	75,10	80 mT 20 min	A	0,996	40 mT 30 min
A	75,03	60 mT 30 min	A	0,988	20 mT 10 min
A	73,50	10 mT 10 min	A	0,977	80 mT 10 min
A	72,00	60 mT 20 min	A	0,920	100 mT 20 min
A	72,00	100 mT 30 min	A	0,895	30 mT 20 min
A	71,63	30 mT 30 min	A	0,883	30 mT 30 min
A	71,50	40 mT 30 min	A	0,858	80 mT 30 min
A	71,25	60 mT 10 min	**A**	**0,849**	**Control**
A	71,00	80 mT 30 min	A	0,837	60 mT 30 min
A	70,17	100 mT 20 min	A	0,791	20 mT 20 min
A	70,00	80 mT 10 min	A	0,780	100 mT 10 min
A	69,76	100 mT 10 min	A	0,774	10 mT 30 min
A	69,08	20 mT 30 min	A	0,768	60 mT 10 min
A	68,75	30 mT 10 min	A	0,763	30 mT 10 min
A	68,25	10 mT 20 min	A	0,762	40 mT 20 min
A	67,50	40 mT 20 min	A	0,737	60 mT 20 min
A	66,75	10 mT 30 min	A	0,728	10 mT 20 min
A	66,09	30 mT 20 min	A	0,713	40 mT 10 min
A	65,25	20 mT 10 min	A	0,704	20 mT 30 min
A	65,13	20 mT 20 min	A	0,691	10 mT 10 min

Table 2-2: Consolidated effect of each magnetic induction with static MF in the germination and vigor index in Tabasco pepper.

Germination %	Treatment	VI	Treatment
75,44	**Control**	0,955	80 mT
72,76	60 mT	0,901	100 mT
72,03	80 mT	**0,849**	**Control**
71,58	40 mT	0,847	30 mT
70,64	100 mT	0,828	20 mT
69,50	10 mT	0,824	40 mT
68,82	30 mT	0,781	60 mT
66,49	20 mT	0,731	10 mT

From the information of the table above it can be inferred that low magnetic induction with static MF (between 10 mT and 30 mT) exerts the most detrimental effects on germination potential, while for vigor index the trend is less clear. However, the ranges already mentioned are also below the control for this parameter.

The latter information reveals that static MF applied to Tabasco pepper seeds caused deleterious effects, predominantly by reducing the percentage of germination and negatively affecting the percentage of vigorous seedlings. Although the differences were not statistically significant in all the cases, the general trend is towards a better physiological performance in seeds not exposed to static MF. By contrast, when treating Habanero seeds with variable MF, it was observed a significant increase in the germination percentage at 25 mT with 10 min of exposition. This treatment also exhibited the highest vigor index, but not significantly different from the control (Table 3-3).

Table 2-3: Germination and vigor index in Habanero pepper seeds treated with variable MF.

Habanero pepper			Habanero pepper		
Duncan	**Germination %**	**Treatment**	**Duncan**	**VI**	**Treatment**
A	91,02	25 mT 10 min	A	0,911	25 mT 10 min
B	85,19	25 mT 20 min	A	0,770	25 mT 20 min
B	**84,47**	**Control**	**A**	**0,753**	**Control**
B	82,65	50 mT 20 min	A	0,748	50 mT 20 min

The previous outcomes are opposite to that reported by several authors (Flórez et al., 2012; Flórez et al., 2007) who found that exposure of different seeds (salvia, calendula, maize) to static MF produced a reduction in the mean germination time and an augment in the percentage of germination. Results of Mridha et al. (2016) even shows that chickpea plants emerged from treated seeds with static MF at 100 mT exhibited higher leaf area, leaf water potential, above-ground biomass and root volume, among other positive effects. This means that the vigor impressed in the early treated seeds is conserved until later stages of the development of the plants.

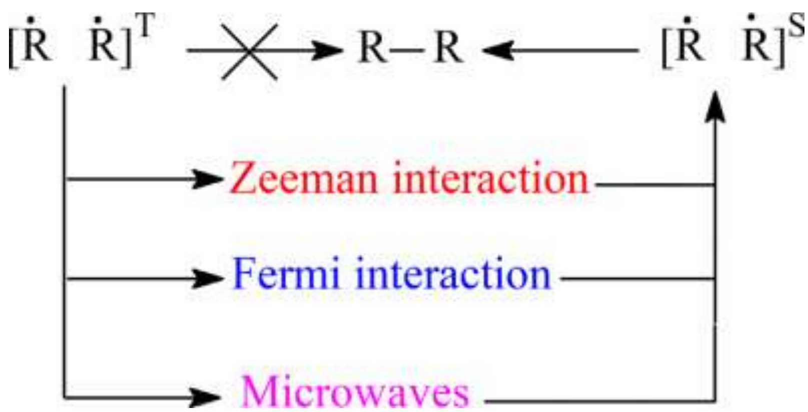
As it is shown in this work, variable MF of different frequency also elicits physiological responses in seeds. Jiménez et al. (2013) have found that variable MF exerts positive effects in the germination process of pepper (*C. chinense*) seeds exposed to variable MF of 60 Hz, more precisely those at 60 mT and 30 mT per 60 min. Notwithstanding, it seems that the application of extremely low MF of low-frequency (0.0015 mT; 10 Hz) also produces significant effects in germinating seeds. In soybean, this treatment elicited important increases in seed viability, height, fresh and dry weight of the plantlets, as well as greater activity of β-amylase and other enzymes (Radhakrishnan and Kumari, 2012).

How to explain these apparent contradictory responses? The lack of agreement between the effects reported here with the previous literature is just another manifestation of the largely known, long and ongoing irreproducibility of magneto-biology phenomena. This is a trend not only circumscribed to plant biology, but also present in other areas such as microbiology and oncology. However, it has been recently explained that this “state of the science” on this issue lays on three sources, related with the radical-pair mechanism of chemical reactions:

> The presence of paramagnetic metal ions as a component of enzymatic site or as an impurity in an uncontrollable amount; the property of the radical pair mechanism to function at a rather high concentration of catalyzing metal ions, when at least two ions enter into the catalytic site; and the kinetic restrictions, which imply compatibility of chemical and spin dynamics in radical pair (Buchachenko, 2016).

The latter author further explain that, regarding oscillating MF, any low-frequency field that oscillates at a frequency higher than the time required for the spin change in the radical pair, can be considered as permanent (or static) fields. Considering this theoretical basis, it is strongly recommended to know accurately the radical-pair reaction mechanism that occurs in germinating seeds, and tune the frequency of the MF to the time of conversion of the triplet and singlet states. The general model of this reaction (which also applies for biochemical reactions) is presented in Figure 3-3.

Figure 2-3: Magnetic interactions with triplet and singlet states in a given reaction. Note that only the singlet state (↑ ↓ opposite spin numbers) is allowed to form the product R-R. Zeeman and Fermi interactions are magnetic and nucleus-related; microwave interaction may change the orientation of the electron spin, but limiting the actual progress of the reaction. Reproduced from Buchachenko (2016).



For example, the enzymatic synthesis of ATP in mitochondria is an ion-radical process because it depends on the magnetic moment and nuclear spin of Mg^{+2} in the enzymes creatine kinase and ATPase. Consequently, the external magnetic field and microwave fields that control the spin states of ion-radical pairs and influence the ATP synthesis can modulate this process (Buchachenko, 2006).

2.5. Conclusions

Variable magnetic fields combined with short exposition times were better in stimulating germination and vigor of Habanero pepper seeds than static MF. Actually, seed treatment with static MF produced negligible or even deleterious effects in the germination process of Tabasco pepper seeds. Magnetic treatment of seeds might be redundant in many cases if the MF do not meet the singlet and triplet state interconversion of the radical-pair biochemical reactions in the germination process of seeds.

3. Magnetic treatment of water enhances net photosynthesis rate and water transport in hydroponically-grown tomato[2]

[2] This section was submitted as an article and is under revision.

4. Photosynthesis and biomass yield in pepper, radish and maize subjected to magnetically-treated water[3]

[3] This section was submitted as an article and is under revision.

5. Magnetically-treated water exhibits lower surface tension and affects physiological processes in Tabasco pepper[4]

[4] This section was submitted as an article and is under revision.

6. Future perspectives and recommendations

The outcomes of this research are a novel contribution on the underlying physiological mechanisms of MTW in plants, which have been elusive for a long time. This will help in the comprehension and appropriation of this technology among crop producers, overcoming the mistrusts and flippancy that have surrounded this issue, sometimes due to a lack of rigorousness in the investigation, and other times because of a natural reluctance to expect magnetic phenomena in water and living beings.

Nonetheless, it is important to point out that the extent of effectiveness of magnetic treatment of water still presents broad variability among different species. This must lead to additional studies either at controlled and field conditions. Such studies should deal with the movement of water in the soil, the evapotranspiration processes, the fluid mechanics of water in the xylem and the stomatal movements. Focusing on the interactions that involve surface tension of magnetically-treated water for irrigation is highly recommended.

Moreover, the marginal effects observed in the magnetic treatment of seeds means that it is not as easy as put them into a magnetic field to increase its vigor, because the physicochemical interactions are largely complex and involve quantic phenomena that should be considered before. Isolated enzymatic reactions-based experiments with magnetic fields could be a proper way to undertake this issue.

A. Annex 1. Physical and chemical properties of the soil used in the experimental section 4 and 5

Parameters	**Units**	**Soil**
CEC	$cmol_c\ Kg^{-1}$	28.9
EC	$dS\ m^{-1}$	0.43
OOC	%	2.57
Texture	-	C-L
pH	-	6.79
EC	$dS\ m^{-1}$	3.7
P	ppm	193.8
S	ppm	16.2
K	$cmol_c\ Kg^{-1}$	1.46
Ca	$cmol_c\ Kg^{-1}$	16.98
Mg	$cmol_c\ Kg^{-1}$	10.19
Na	$cmol_c\ Kg^{-1}$	0.26
(Ca+Mg)/K	-	29.78
Mn	ppm	71.4
B	ppm	0.32
Zn	ppm	6.82
Cu	ppm	4.68
Fe	ppm	17.2

Source: Agrilab. Data are means of 5 sample points (lab consecutive numbers from 119365 to 119366).

B. Annex 2. Some pictures of the experimental setup

b

Hydroponic system with recirculation of water in growth room. A: Quantum Biotek magnet (MTW). B: PVC joint (control). Arrows shows loop water flow (photo: Daniel Ospina).

Experimental setup of Tabasco pepper in net house (photo: Daniel Ospina).

Experimental setup of red radish in net house. A: randomized drip irrigation system (photo: Daniel Ospina).

Experimental setup of yellow maize in net house (photo: Daniel Ospina).

Germination analysis of Tabasco pepper seeds in moistened rolled paper (photo: Daniel Ospina).

C. Annex 3. Recirculation system for magnetic treatment of water

A: water pump. B: Quantum Biotek magnet. C: reservoir. D: bypass without magnet for control. Arrows show water flow. Left picture shows open valves for irrigation. Right picture shows closed valves for water recirculation through the magnet (photo: Daniel Ospina)

D. Annex 4. Influence of a magnetic field on the stress tensor of a viscous fluid confined in a cylindrical vessel[5]

1. Definition of magnetic field

A magnetic field (MF) is the mathematical description of the magnetic influence of electric currents and magnetic materials. A MF is a vector field. To describe a MF **B** in a given region of the space (see Figure 2-1) it is considered that:

- A test charge q is released across a given point with a velocity $\mathbf{v}$. If there is present a magnetic force $\mathbf{F}$**,** it would act so that $\mathbf{F}\perp\mathbf{v}$.

- As the direction of $\mathbf{v}$ is varied, the magnitude of $\mathbf{F}$ changes from zero when $\mathbf{v}$ has certain direction until reaching a maximum when $\mathbf{F}\perp\mathbf{v}$.

- Between halfway angles, the magnitude of $\mathbf{F}$ varies according to $\sin\varphi$ between $\mathbf{v}$ and $\mathbf{F}$.

- It is observed that $\mathbf{F}$ is proportional to the magnitude of q and that its direction is inverted if the sign of q is changed.

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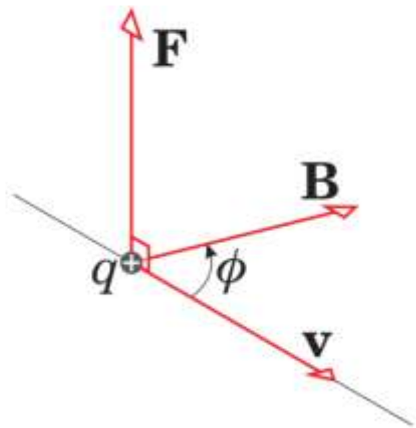
[5] The sections of this chapter are based total or partially on the following: **1**: Lugo-Licona, 2006. **2**: Landau and Lifshitz, 1987. **3**: Jackson, 1962. See references.

- The direction of $\mathbf{B}$ is the same as one of the directions of $\mathbf{v}$ for which $\mathbf{F} = \mathbf{0}$ and the magnitude of $\mathbf{B}$ is given by the magnitude $\mathbf{F}\perp$ of the maximum force performed when the test charge is released in a perpendicular direction to $\mathbf{B}$, so that $\mathbf{B} = \frac{\mathbf{F}\perp}{q}$

Figure D-1: A positive-charged particle q moving at velocity $\mathbf{v}$ across a space with MF $\mathbf{B}$ will experience a diverting force $\mathbf{F}$ (image from Lugo-Licona, 2006).

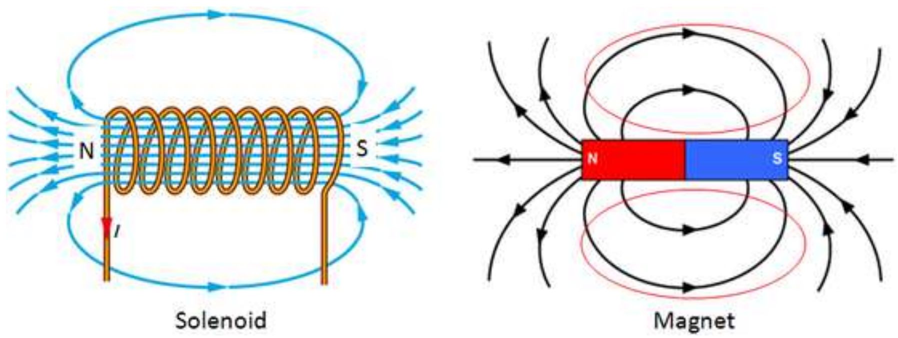


For arbitrary angles: $\mathbf{F} = \frac{q}{c}\mathbf{vB}\sin\varphi$, where φ is the smallest angle between $\mathbf{v}$ and $\mathbf{B}$. Therefore, the force performed on the particle with charge q because of the influence of the electric field $\mathbf{E}$ and the MF $\mathbf{B}$ is defined according to the Lorenz force (eq. 1) as a function of the force performed on the mobile charge:

$$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) \qquad \text{(Eq. 1)}$$

The MF unit in the International System is the tesla (T), defined as the MF that performs a force of 1 N (newton) on a charge of 1 C (coulomb) that moves at a velocity of 1 m s^{-1} within the MF and perpendicular to the MF lines, which are represented in Figure 2-2.

Figure D-2: Representation of the magnetic field lines in a solenoid (a spiral of conductor wire) and a magnet (image courtesy of OnlinePhys and http://www.excelatphysics.com).



2. Stress tensor

Here, it is analyzed the effect of the dissipation energy that occurs during fluid movement. This process is the result of the thermodynamic irreversibility of the motion. The irreversibility always takes place along the fluid and is a manifestation of the internal friction of the particles (viscosity) and the thermal conductivity.

The equation of continuity is also valid for any fluid, whether is viscous or not. The Euler's equation is written in the form:

$$\frac{\partial}{\partial t}(\rho \mathbf{v}_{\boldsymbol{i}}) = -\frac{\partial \prod_{ik}}{\partial x_k} \qquad \text{(Eq. 2)}$$

Where $\prod_{ik}$ is the tensor of momentum of flux density. The equation of the movement of a viscous fluid can be obtained by addition of the momentum of an "ideal" flux with term $-\sigma'_{ik}$, being σ'_{ik} the *viscous stress tensor* and $\mathbf{p}\ \delta_{ik}$ the *hydrostatic pressure* of the fluid.

$$\prod_{ik} = \mathbf{p}\ \delta_{ik} + \rho \mathbf{v}_i \mathbf{v}_k - \sigma'_{ik} = -\sigma'_{ik} + \rho \mathbf{v}_i \mathbf{v}_k \qquad \text{(Eq. 3)}$$

The *stress tensor* is given by the equation:

$$\sigma_{ik} = -\rho \mathbf{v}_i \mathbf{v}_k + \sigma'_{ik} \qquad \text{(Eq. 4)}$$

The term σ'_{ik} can be represented in the form of a lineal function of the derivatives $\frac{\partial \mathbf{v}_i}{\partial x_k}$. The general form for the *viscous stress tensor* is:

$$\sigma'_{ik} = \eta\left(\frac{\partial \mathbf{v}_i}{\partial x_k} + \frac{\partial \mathbf{v}_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial \mathbf{v}_l}{\partial x_l}\right) + \zeta\delta_{ik}\frac{\partial \mathbf{v}_l}{\partial x_l} \qquad \text{(Eq. 5)}$$

Being η and ζ the coefficients of viscosity of the fluid and independent of the velocity, both positive.

Therefore, the stress tensor is written as:

$$\sigma_{ik} = -\mathbf{p}\,\delta_{ik} + \sigma'_{ik} \qquad \text{(Eq. 6)}$$

3. Maxwell's stress tensor

According to the Newton's second law, the force of the MF shown in eq. 1 can be written as follows:

$$\frac{d\mathbf{P}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) \qquad \text{(Eq. 7)}$$

Naming as $\mathbf{P}_{mech}$ the sum of all the momenta of the whole particles contained in a volume V, this yields:

$$\frac{d\mathbf{P}_{mech}}{dt} = \int_V \left(\rho\mathbf{E} + \frac{1}{c}\mathbf{J} \times \mathbf{B}\right) d^3x \qquad \text{(Eq. 8)}$$

The extended sum to the particles has been converted into an integral extended to the densities of charge and current. Maxwell's theorem is used to eliminate ρ and $\mathbf{J}$:

$$\rho = \frac{\mathbf{1}}{\mathbf{4\pi}}\nabla \cdot \mathbf{E} \quad \text{and} \quad \mathbf{J} = \frac{\boldsymbol{c}}{\mathbf{4\pi}}\left(\nabla \times \mathbf{B} - \frac{\mathbf{1}}{\boldsymbol{c}}\frac{\partial \mathbf{E}}{\partial t}\right) \qquad \text{(Eq. 9)}$$

In the equations 9 it is considered only $\mathbf{E}$ and $\mathbf{B}$ because all the charges are involved in the mechanical part of the system.

Replacing the equations 9 in the equation 8 the integrating is transformed into:

$$\rho\mathbf{E}+\frac{1}{c}\mathbf{J}\times\mathbf{B}=\frac{1}{4\pi}\left[\mathbf{E}(\boldsymbol{\nabla}\cdot\mathbf{E})+\frac{1}{c}\mathbf{B}\times\frac{\partial\mathbf{E}}{\partial t}-\mathbf{B}\times(\boldsymbol{\nabla}\times\mathbf{B})\right] \qquad \text{(Eq. 10)}$$

Taking into account that:

$$\mathbf{B}\times\frac{\partial\mathbf{E}}{\partial t}=-\frac{\partial}{\partial t}(\mathbf{E}\times\mathbf{B})+\mathbf{E}\times\frac{\partial\mathbf{B}}{\partial t}$$

And adding $\mathbf{B}(\boldsymbol{\nabla}\cdot\mathbf{B})=\mathbf{0}$ into the brackets in the equation 10 it is obtained:

$$\rho\mathbf{E}+\frac{1}{c}\mathbf{J}\times\mathbf{B}=\frac{1}{4\pi}[\mathbf{E}(\boldsymbol{\nabla}\cdot\mathbf{E})+\mathbf{B}(\boldsymbol{\nabla}\cdot\mathbf{B})-\mathbf{E}\times(\boldsymbol{\nabla}\times\mathbf{E})-\mathbf{B}\times(\boldsymbol{\nabla}\times\mathbf{B})]-\frac{1}{4\pi c}\frac{\partial}{\partial t}(\mathbf{E}\times\mathbf{B})$$

From the latter it is obtained the equation 11, which corresponds to the variation of mechanical momentum with time:

$$\frac{d\mathbf{P}_{mec}}{dt}+\frac{d}{dt}\frac{1}{4\pi}\int_V\frac{1}{4\pi}(\mathbf{E}\times\mathbf{B})=\frac{1}{4\pi}\int_V[\mathbf{E}(\boldsymbol{\nabla}\cdot\mathbf{E})-\mathbf{E}\times(\boldsymbol{\nabla}\times\mathbf{E})+\mathbf{B}(\boldsymbol{\nabla}\cdot\mathbf{B})-\mathbf{B}\times(\boldsymbol{\nabla}\times\mathbf{B})]d^3x$$

(Eq. 11)

It is possible to identify the volume integral of the first member as the total electromagnetic momentum $\mathbf{P}_{field}$ in the volume V:

$$\mathbf{P}_{field}=\frac{1}{4\pi c}\int_V(\mathbf{E}\times\mathbf{B})d^3x \qquad \text{(Eq. 12)}$$

The integrand can be considered as the density of electromagnetic momentum.

It is clear that the terms of the volume integral in the equation 12 are transformed in vectors, so that it is possible to combine them in order to be a 2nd order tensor, and this tensor can be processed in the frame of vector operation introducing the respective dyadic.

Designating a three-dimension tensor as $T_{ij}=(i,j=1,2,3)$ and $\boldsymbol{\varepsilon}_i$ as the unit base vectors of the coordinate system, the correspondent dyadic of the tensor T_{ij} is defined as:

$$\overleftrightarrow{\mathbf{T}} = \sum_{i=1}^{3} \sum_{j=1}^{3} \boldsymbol{\varepsilon}_i \boldsymbol{T}_{ij} \boldsymbol{\varepsilon}_j \text{ (Eq. 13)}$$

The elements of the tensor can be determined by taking suitable scalar products:

$$T_{ij} = \boldsymbol{\varepsilon}_i \cdot \overleftrightarrow{\mathbf{T}} \cdot \boldsymbol{\varepsilon}_j \text{ (Eq. 14)}$$

A special dyadic is the identity $\overleftrightarrow{\mathbf{I}}$ formed with the unit second-rank tensor:

$$\overleftrightarrow{\mathbf{I}} = \boldsymbol{\varepsilon}_1\boldsymbol{\varepsilon}_1 + \boldsymbol{\varepsilon}_2\boldsymbol{\varepsilon}_2 + \boldsymbol{\varepsilon}_3\boldsymbol{\varepsilon}_3 \qquad \text{(Eq. 15)}$$

Based on the vector identity and proceeding with the vector manipulations needed to convert the volume integral of the right side:

$$\frac{1}{2}\boldsymbol{\nabla}(\mathbf{B}\cdot\mathbf{B}) = (\mathbf{B}\cdot\boldsymbol{\nabla})\mathbf{B} + \mathbf{B}\times(\boldsymbol{\nabla}\times\mathbf{B})$$

The terms involving $\mathbf{B}$ in the equation 6 can be written:

$$\mathbf{B}(\boldsymbol{\nabla}\cdot\mathbf{B}) - \mathbf{B}\times(\boldsymbol{\nabla}\times\mathbf{B}) = \mathbf{B}(\boldsymbol{\nabla}\cdot\mathbf{B}) + (\mathbf{B}\cdot\boldsymbol{\nabla})\mathbf{B} - \frac{1}{2}\boldsymbol{\nabla}B^2 \qquad \text{(Eq. 16)}$$

This can be identified as the divergence of a dyadic:

$$\mathbf{B}(\boldsymbol{\nabla}\cdot\mathbf{B}) + (\mathbf{B}\cdot\boldsymbol{\nabla})\mathbf{B} - \frac{1}{2}\boldsymbol{\nabla}B^2 = \boldsymbol{\nabla}\cdot\left(\mathbf{B}\cdot\mathbf{B} - \frac{1}{2}\overleftrightarrow{\mathbf{I}}B^2\right) \qquad \text{(Eq. 17)}$$

Because of the conservation of linear momentum becomes:

$$\frac{d}{dt}\left(\mathbf{P}_{\boldsymbol{mech}} + \mathbf{P}_{\boldsymbol{field}}\right) = \int_V \boldsymbol{\nabla}\cdot\overleftrightarrow{\mathbf{T}}\, d^3x = \oint_S \mathbf{n}\cdot\overleftrightarrow{\mathbf{T}} da \qquad \text{(Eq. 18)}$$

The tensor $\overleftrightarrow{\mathbf{T}}$ is called *Maxwell's stress tensor* and is defined as:

$$\overleftrightarrow{\mathbf{T}} = \frac{1}{4\pi}\left[\mathbf{EE} + \mathbf{BB} - \frac{1}{2}\overleftrightarrow{\mathbf{I}}(E^2 + B^2)\right] \qquad \text{(Eq. 19)}$$

The elements of the tensor are:

$$T_{ij} = \frac{1}{4\pi}\left[E_iE_j + B_iB_j - \frac{1}{2}\delta_{ij}(E^2 + B^2)\right] \qquad \text{(Eq. 20)}$$

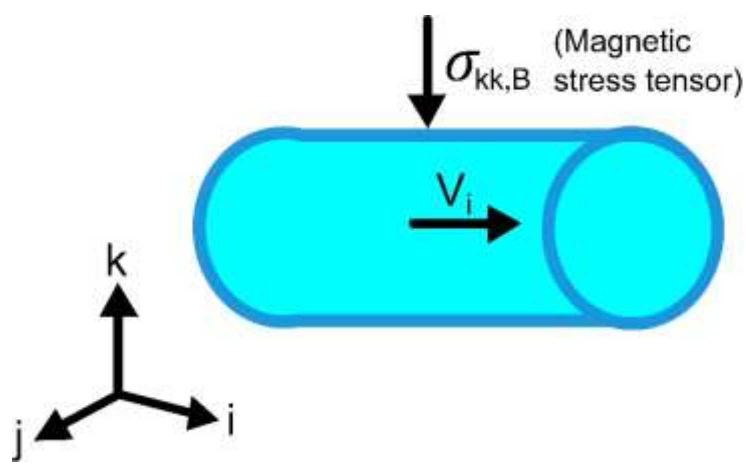
For the specific case of the influence of a MF on the stress tensor of a fluid it is only considered the MF $\mathbf{B}$, hence, the electric field $\mathbf{E} = \mathbf{0}$. Therefore, the equation 19 that defines the elements of the Maxwell's tensor can be summarized in the equation 21:

$$T_{ij} = -\frac{1}{8\pi}B^2 \qquad \text{(Eq. 21)}$$

Which finally becomes as the *Magnetic stress tensor (*Figure 2-3) in the form:

$$\sigma_{\ kk,\mathbf{B}} = -\frac{1}{8\pi}B^2 \qquad \text{(Eq. 22)}$$

Figure D-3: Maxwell's magnetic stress tensor working on a moving fluid with velocity $\mathbf{v}_{\mathrm{i}}$.



In common practice the MF can be defined in terms of the *intensity of the magnetic field* $\mathbf{H}$ (units $T = {}^{N}/_{mA}$), according to the relation:

$$\mathbf{B} = \frac{\mathbf{H}}{\mu_0} \qquad \text{(Eq. 23)}$$

Being μ_0 the permeability of free space (in $^{N}/_{A^2}$); therefore, the equation 22 of the magnetic stress tensor can be written as:

$$\sigma_{kk,\mathbf{B}} = -\frac{1}{8\pi}\left(\frac{\mathbf{H}}{\mu_0}\right)^2 \qquad \text{(Eq. 24)}$$

Thus, the magnetic tensor $\sigma_{kk,\mathbf{B}}$ has units of $^{N}/_{m^2}$ correspondent to pressure units.

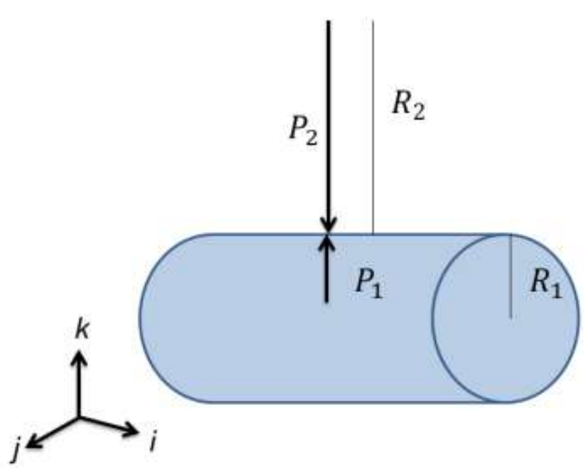
4. Total stress tensor in a fluid under the influence of a MF

In order to define the *Total stress tensor in a fluid* it has to be considered the stress tensor σ_{ik} and the magnetic stress tensor $\sigma_{kk,\mathbf{B}}$.
Likewise, there must be considered the *Surface stress tensor, which* is based on the Laplace's formula (equation 25) that shows the pressure that occurs in the surface of a liquid inside a cylindrical vessel:

$$P_1 - P_2 = \alpha\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad \text{(Eq. 25)}$$

Where α is the *surface tension* of the liquid and R is the relation between the internal and external radius of the fluid (Figure 2-4).

Figure D-4: Pressures on a liquid that is inside a cylindrical vessel of radius R.



Because the radius R_2 is much higher that R_1 the term $\frac{1}{R_2}$ is became to zero, thus it is possible to define the surface stress tensor as:

$$\overleftrightarrow{\mathbf{S}} = -\frac{\alpha}{R}\sigma_{\ ik} \qquad \text{(Eq. 26)}$$

Finally, with the sum of the tensors defined in the equations 6, 24 and 26 it is obtained the ***Total stress tensor on a fluid in relation with the MF,*** whose equation is:

$$\sigma_{\ Total} = -\mathbf{p}\,\delta_{ik} + \sigma'_{\ ik} + \sigma_{\ kk,\mathbf{B}} - \frac{\alpha}{R}\sigma_{\ ik} \qquad \text{(Eq. 27).}$$

Where:

- $-\mathbf{p}\,\delta_{ik}$ is the hydrostatic pressure generated inside the fluid.
- $\sigma'_{\ ik}$ is the *viscous stress tensor* that is a function of the dynamic properties of the fluid.
- $\sigma_{\ kk,\mathbf{B}}$ is the *magnetic stress tensor* performed by the MF around the fluid.
- $-\frac{\alpha}{R}\sigma_{\ ik}$ is the *surface stress tensor* that is performed by a force on the surface of the fluid, which generates a shear stress that is related with the surface tension α inherent of each fluid.

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